

# Formation of Massive Black Holes in Early Mergers ?

Hartmut Schulz<sup>1</sup> and Stefanie Komossa<sup>2</sup>

<sup>1</sup> Astron. Inst. Ruhr University, D-44780 Bochum, Germany

<sup>2</sup> MPI f. extraterrestrische Physik, PF 1603, D-85740 Garching, Germany

**Abstract.** We review theoretical and observational arguments favoring a scenario in which a typical massive black hole (MBH) is formed in the merger core of colliding disk systems at high  $z$  during the build-up of a spheroid. Low-mass ( $\sim 10^{5-6} M_{\odot}$ ) *seed* black holes are assumed to have been formed earlier. The most massive black holes giving rise to the most luminous active galactic nuclei (AGN) in active phases are expected to grow in violent mergers of large disk-plus-bulge systems that lead to giant elliptical galaxies, the typical hosts of radio galaxies and quasars. We consider current ultraluminous infrared galaxies (ULIRG) as systems closely resembling the predecessors of early formed massive ellipticals. As an example, we discuss the evidence for an AGN in the merging system NGC 6240 which we advertize as a prototypical active ULIRG, obscured in X-rays by a high column density absorber.

## 1 Formation of spheroids and compact cores

There is ubiquitous evidence for the presence of massive (and mostly “dark”) *compact* cores with  $M = 10^{6-10} M_{\odot}$  in the nuclei of nearby galaxies [47]. A few of these objects, like NGC 4258 [64] or the Galactic center [25], are generally considered to be nearly inevitably explained by MBHs although a ‘burning disk’ (BD) ([48], and Kundt, this conference) has been proposed as an alternative. Since convincingly detailed models for both the formation of a MBH or a BD are still lacking, a clear-cut decision cannot be made without further arguments. One argument relies on the observationally deduced mass-energy conversion efficiency that will be briefly discussed in Sect. 1.3 below. Other common, albeit not fully compelling, arguments in favor of MBHs are based on variability studies and apparent superluminal expansion [11].

Below we simply follow the standard practice to identify the detected *massive compact objects* with MBHs and discuss theoretical and observational arguments concerning their formation. A large part of the discussion can be applied to any massive compact object which is potentially able to promote the non-stellar activity observed in AGNs.

The most general prerequisites for the formation of a MBH are (i) the presence of enough material to be compressed; (ii) an efficient mechanism to cool the material during collapse in order to remove the released gravitational energy which could otherwise inhibit the final collapse; (iii) an efficient mechanism to transfer angular momentum outwards so that the inner parts of the forming disk will be able to continue accreting material from the outer

parts. Formation of a ‘true’ MBH means that all barriers have been overcome, also the possible barrier put up by commencing nuclear burning. To a certain extent, conditions (i) – (iii) have to be fulfilled for the formation of stars, galaxies or BDs as well.

In galaxy formation one distinguishes between *dissipationless* and *dissipative* collapse. A *collisionless* system of particles, e.g. a stellar system or weakly interacting dark matter, can collapse without dissipation whereas common baryonic gas is able to *cool*, i.e. lose energy that has been gained during gravitational contraction. Domains in the temperature-density diagram provide insight into the potential behavior of a protogalactic gas cloud [71]. Transforming the ‘cooling curves’ ( $t_{\text{cool}} = t_{\text{dyn}}$ ) into a velocity dispersion - density diagram shows which objects had been formed in a dissipative manner [46]. Cores of elliptical galaxies underwent strongly dissipative collapse. Black hole formation requires strong dissipation. In the standard picture, the glowing accretion disks of quasars (we subsume under the term ‘quasars’ radio loud *and* radio quiet objects) are the signatures of dissipative *growth* of black holes.

### 1.1 Black hole formation

MBHs are widely believed to be the prime mover of non-stellar activity in galactic nuclei (i.e. in AGN; cf. [70], [11]). Dynamical evidence for MBHs has been found in a number of nearby galaxies [47]. However, the origin of MBHs is still enigmatic. A fundamental problem is to form a *seed* black hole which would subsequently grow more easily if material can be dumped down to it. Massive seed black holes may have formed (A) either directly after structure formation had entered its epoch of non-linear collapse or (B) later via the collapse of mature baryonic gas clouds or stellar clusters. Evidence for MBHs has so far been only found in galactic nuclei. Therefore scenario (A) should be related to a pre-stage or early stage of *formation* of galaxies while (B) has to take place during the *evolution* of galaxies. It may be interesting that luminous AGN have so far been found up to redshifts of  $\sim 5$ , luminous quasars show indications of metal abundances higher than solar [37] and that non-AGN galaxies have already been detected at  $z > 6$ . Also, radio surveys (which are much less prone to ‘hiding effects’ as, e.g., by dust obscuration) confirm a general decline of the comoving quasar space density beyond  $z \sim 3$  so that “ $z > 5$  quasars must be rare” [80]. If intergalactic hydrogen gas were neutral at these redshifts, strong absorption shortward of Ly $\alpha$  would be expected in high- $z$  quasars [35] which is not observed calling for a *reionization* epoch after cosmological (re)combination. Only young stars are left as major ionizing agent so that we are, altogether, led to a scenario in which an epoch of appreciable star formation precedes MBH formation.

Tidal interaction of collapsing objects with their surroundings leads them to acquire angular momenta which provide a centrifugal barrier. To circumvent this problem (the above condition (iii)) early ideas centered on Compton

drag to the electrons of the collapsing cloud caused by the Cosmic Background Radiation [54]. This mechanism could already work at redshifts between  $\sim 200$  and the epoch of recombination provided that sufficient reionization takes place. For the average angular momenta expected, less exotic mechanisms like turbulent viscosity appear to be too slow for typical galactic disks if they are the only agent for a torque [55]. To overcome the centrifugal barrier Eisenstein & Loeb (1995, [26]) focused on the *low-spin tail* of the distribution of angular momenta, i.e. on objects that have such a low angular momentum that a semi-relativistic disk with a short viscous time is formed which inevitably evolves to a black hole. Locations with unusually small tidal torques are expected to be present, and Eisenstein and Loeb estimate that the low-spin objects should be abundant enough to produce  $\sim 10^6 M_\odot$  seed black holes beyond  $z \sim 10$  with a comoving density comparable to that of bright galaxies.

The growth of black holes or even the formation of MBHs via scenario (B) can be triggered by non-axisymmetric perturbations induced by bars (for a good review cf. Larson 1994 [50]) or by tidal interactions (e.g. [5]). While the usual global low-resolution numerical calculations verify these mechanisms to be capable to dump down material into the innermost central kiloparsec of a galaxy it is less clear how to reach smaller scales. Bekki (1995 [7]) followed the dynamical evolution of two merging galactic cores and found that gas can be transferred efficiently to the innermost 50 pc if the cores are rather compact and contain excessively large amounts of gas. Inside 50 pc a MBH exceeding  $\sim 10^8 M_\odot$  would dominate the dynamics. Scenario (B), i.e. the actual formation of a MBH, would however require to bridge the scale down to a Schwarzschild radius against a remaining centrifugal barrier and the tendency of the gas to fragmentation.

A different version of scenario (B) would be to form a MBH by a collapse of a system of more compact objects, e.g. a dense stellar cluster, rather than from diffuse gas. This channel was one of those conjectured for AGNs by Rees in 1984 [70] and earlier. More details about the growth of a MBH were studied by David et al. (1987 [19]). A scenario of the subsequent evolution as influenced by the circumnuclear stellar population was described by Norman & Scoville (1988 [68]). Too dense stellar clusters have a low lifetime due to frequent stellar collisions, and it is actually this argument to infer the presence of MBHs rather than compact stellar clusters in the nuclei of NGC 4258 [62] and our Galaxy [25].

To summarize: Very early AGNs ( $z > 5$ ) seem to be rare. If there is no strong agent inhibiting accretion at that time, this also applies to MBHs. Small black holes with  $M \sim 10^{5-6} M_\odot$  may be present at that time because they would give rise to low-luminosity AGN likely to be outshone by star-forming sources. These small black holes are welcome to form the *seeds* for subsequent growth to MBHs which we shall discuss below. The *'seedless' birth* of MBHs in present-day galaxies would be difficult from diffuse gas, but

can be imagined as the final result of star-cluster evolution provided that a sufficiently dense cluster can be produced.

## 1.2 Formation of galaxies

AGNs exist in spiral galaxies (most Seyfert galaxies are spirals) but the most luminous activity and, via Eddington-luminosity arguments, indicative of the most massive black holes is commonly found in ellipticals (quasars and classical radio galaxies) [10]. Evidence for MBHs in nearby galaxies has been detected mostly in weakly active spirals, interpreted as ‘dormant’ black holes starving of fuel or surrounded by an ‘advective’ [1] [65] accretion disk. This suggests that MBHs are more frequent than clear-cut AGNs.

Although selection effects are present, the mass of the MBH in nearby galaxies appears to be correlated with the mass or  $B$ -magnitude or core radio power of the spheroidal component (either bulge or the elliptical) (e.g. [30]). Relationships of AGN features with bulge properties have long been noted in Seyfert galaxies [66]. Hence, we take it as a likely working hypothesis that MBHs are related to the formation history of a spheroid.

Recent statistics on the morphology of bulges has unveiled a variety of asymmetries that suggest that these components were not formed via a single collapse and have relaxed since then. Rather a picture in terms of gravitational interactions emerges in which the least violent ones lead to bar formation and the subsequent development of box and peanut bulges while stronger interactions lead to thick boxy bulges [21], [56].

On the other hand, classical textbook arguments emphasize that ellipticals contain an old, relatively homogeneous, stellar population. Hence, it appeared that ellipticals had been formed ‘at one stroke’, by a single collapse of low-angular momentum material followed by ‘violent relaxation’ and subsequent essentially passive evolution [49].

Within the last decade, more and more data and calculations have supported the so-called ‘merger hypothesis’ which implies that many ellipticals formed from the collision of disk objects. The occasional occurrence of faint shells, tidal tails or ripples [78], [75] and systems of young globular clusters [79] provide observational support for this hypothesis. Further confirmation is lent by the high stellar velocity dispersion that has been measured in a few nearly completed mergers. However, this does *not* necessarily mean that *all* ellipticals evolved from mergers.

In clusters, less violent interactions, e.g. tidal stripping, are likely to transform disk galaxies into S0s and ‘disky’ ellipticals [73]. Here, the central giant elliptical (or cD) is the most likely to have evolved via merging. This is the strongest X-ray source and often a radio galaxy, which is in the standard AGN theory a clear indication for the presence of a MBH. In general, luminous ‘boxy’ ellipticals show the best observational clues for a merger history [9].

The scenario cannot be too simple because metal abundance ratios *rule out* that *massive ellipticals* could be the product of dissipationless mergers of *present-day* spirals. To explain their Mg/Fe-ratios a preponderance of type II supernovae in a star formation time scale of  $\sim 1$  Gyr is required [8]. If this were only confined to the core this might be explained by violent starburst activity in the central molecular gas accumulated during the merging event (see below). However, the observers see these abundance ratios as a global phenomenon of the galaxies so that we can only maintain the merger scenario if these early merging spirals differ significantly from current nearby spirals.

Numerical simulations of encounters between massive disk galaxies are able to reproduce the formation of an elliptical. A fine example is given in [5] where a collision between two milky-way type galaxies leads within  $1.5 \cdot 10^9$  yrs to the deposition of 60% of all the diffuse gas of the two galaxies in the central kiloparsec of the merger. The stars acquire a distribution typical for an elliptical. The gas could reach the center because conditions (ii) (strong radiative cooling) and (iii) (strong gravitational torques) were fulfilled. If the cooling were switched off the released gravitational energy would have heated the gas so strongly that a giant X-ray bubble of more than 40 kpc radial extent would have been produced (Fig. 13 in [5]). We speculate that incomplete cooling could have led to the ‘seed bubbles’ of current extended X-ray sources around ellipticals.

The spatial resolution of the encounter simulations is usually not good enough to predict the future of the centrally collected gas. It is expected that the gas contracts further and forms fragments so that a burst of star formation will occur. After this stage, either a MBH may be formed (see Sect. 1.1) or a seed black hole might be fed and become more massive.

In any case, the so-called *ultraluminous infrared galaxies* (ULIRG; galaxies with a total IR luminosity exceeding  $10^{12} L_{\odot}$ ) exhibit the features theoretically expected: usually they appear to be mergers [95] and they contain about  $10^{10} M_{\odot}$  of molecular gas within the central  $10^{2-3}$  pc (e.g. [85]). These objects have a space density in the nearby universe comparable to that of ‘local’ quasars of the same  $L_{\text{bol}}$  [74], [42] suggesting a link to luminous AGNs.

Radio galaxies are of special interest because, in the standard picture, they are safe to contain an AGN and a MBH. At  $z > 3$ , their rest-frame optical morphology reveals several 10-kpc components, apparently dominated by recent star formation, and partially aligned with the radio structures [88]. Hence, it appears that at  $z > 3$  the massive ellipticals form hierarchically. At these high redshifts radio galaxies seem to evolve into more massive systems than radio-quiet objects.

Putting all the observational evidence together, present-day galaxies appear to have formed and evolved during an extended merging and star formation history, with massive ellipticals usually having completed the more violent parts of their history earlier, in particular the formation of their old stellar populations. This rough picture resembles the more detailed theo-

retical scenarios of hierarchical galaxy formation in CDM halos pioneered by White and Rees [92] and subsequently advanced, among others, by the Durham and Garching groups [6]. Seed MBHs are formed early (at high  $z$ ) and the observed correlations suggest that they grow roughly in proportion to the spheroidal component. Whether slow ‘adiabatic’ growth in a relaxed galaxy [94] or galaxy formation around a pre-existing MBH [84], takes place cannot yet be decided because both scenarios lead to similar end states as was pointed out by van der Marel [89].

How much time is available for the formation of spheroids and active cores? In Table 1 we give ages as a function of  $z$  for two types of unaccelerated universes: The flat Einstein–de Sitter world model with  $q_0 = 0.5$  and, to get large time scales, the limiting open model with  $q_0 = 0$ . Even though we

**Table 1.** Age of the universe since big bang (for  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ )

Redshift $z$	for $q_0 = 0.5$ (years)	for $q_0 = 0$ (years)
0	$13.0 \cdot 10^9$	$19.6 \cdot 10^9$
1	$4.6 \cdot 10^9$	$9.8 \cdot 10^9$
3	$1.6 \cdot 10^9$	$4.9 \cdot 10^9$
5	$8.9 \cdot 10^8$	$3.3 \cdot 10^9$
20	$1.4 \cdot 10^8$	$9.3 \cdot 10^8$
100	$1.3 \cdot 10^7$	$1.9 \cdot 10^8$
1000	$4.1 \cdot 10^5$	$1.9 \cdot 10^7$

adopted a low Hubble constant, Table 1 shows that there is hardly more time than  $\sim 10^9$  yrs to form galaxies at  $z \sim 3 - 5$ . To assemble a galaxy with  $M > 10^{11} M_\odot$  in  $10^9$  yrs one needs star formation rates  $> 10^2 M_\odot \text{ yr}^{-1}$ . In the present-day universe only ULIRGs have such star formation rates, again suggesting that the predecessors of early ellipticals bear similarities to ULIRGs.

However, such time-scale arguments are weakened if the classical standard world models (that are dominated by gravitational braking) do not apply. Accelerated world models would have a larger age at same  $H_0$  and, from high- $z$  supernovae, there is mounting evidence for a general acceleration (cf. Ruiz-Lapuente, this conference)

### 1.3 The space density of MBHs

The present energy density  $u$  of quasar radiation amounts to  $u \sim 1.3 \cdot 10^{-15}$  erg cm $^{-3}$  ([83], [16], [86]) leading via standard accretion theory to an average mass density in black hole mass

$$\rho_{\text{MBH}} = \frac{u}{\epsilon c^2} \approx 2.2 \cdot 10^5 \left( \frac{0.1}{\epsilon} \right) M_{\odot} \text{Mpc}^{-3} \quad (1)$$

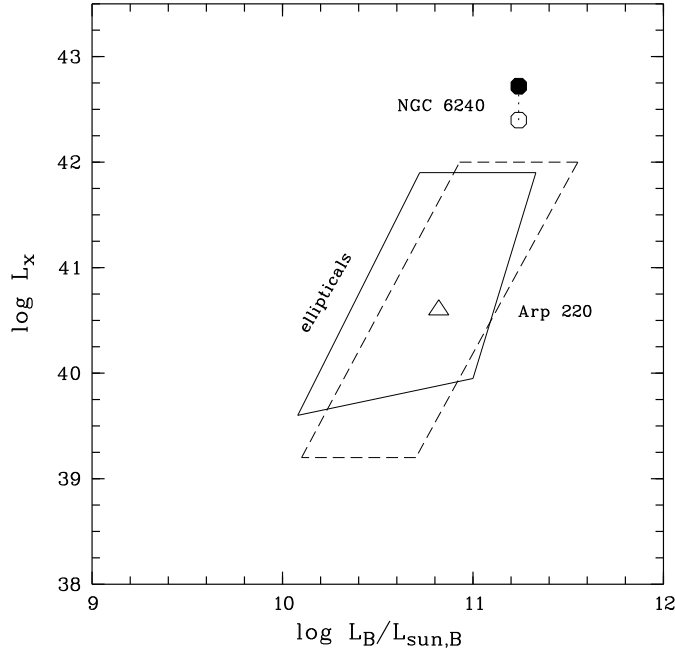
( $\epsilon$  is the accretion energy conversion efficiency, which we assume to be of the order of  $\sim 0.1$ ). With  $10^{-2}$  to  $10^{-1}$  bright galaxies per Mpc $^3$  (see, e.g. Fig. 1 in [74]) one obtains  $M_{\text{MBH}} \sim 10^{7-8} M_{\odot}$  per bright galaxy. In the local universe Seyferts are the most abundant AGNs. Since at most only a few percent of the spirals are known Seyferts, most MBHs appear to be currently inactive (or weakly active if we count the LINERs as AGNs), i.e. ‘dormant quasars’, as is also indicated by the kinematical MBH searches. Although such estimates bear considerable uncertainties it appears clear that MBHs must be a frequent component of the cores of galaxies. If the statistics were requiring an  $\epsilon$  close to the nuclear-fusion efficiency the black-hole scenario would become less compelling as was pointed out by Kundt [48].

Simple arguments from accretion theory suggest that the *total active lifetime* of a quasar or AGN cannot exceed  $\sim 10^{8-9}$  yrs. For example, imagine a typical quasar with  $L_{\text{bol}} = 10^{46}$  erg s $^{-1}$  which requires an accretion rate of  $\sim 1 M_{\odot} \text{yr}^{-1}$  so that  $10^8 M_{\odot}$  will be built up within  $10^8$  yrs. Note, that the Eddington luminosity of  $10^8 M_{\odot}$  is just  $L_{\text{Edd}} = 10^{46}$  erg s $^{-1}$  and that actual luminosities are slightly above  $L_{\text{Edd}}$ . The argument can be easily generalized (Sect. 4.3) and holds as long as the accretion rate is not far below ‘Eddington’. The fraction AGN-lifetime/Hubble time fits to the fraction of AGNs among galaxies.

## 2 Extended X-ray sources around ellipticals

Up to a few keV the total X-ray luminosities of bright ‘normal’ spiral galaxies are below  $\sim 10^{40-41}$  erg/s and the radiation can be traced back to a number of discrete sources inside the galaxies as was verified in nearby galaxies [27]. In this case the increase of  $L_X$  with the total blue luminosity  $L_B$  of the galaxies is relatively flat.

On the other hand, ellipticals are generally surrounded by X-ray bright extended sources with  $L_X \sim 10^{39-42}$  erg/s that are relatively well established *thermal* sources in luminous cases.  $L_X$  shows a steep increase with  $L_B$  (Fig. 1). For a few cluster ellipticals  $L_X$  of the extended source exceeds  $10^{42}$  erg/s which is, however, attributed to the ‘contamination’ by the hot intergalactic medium of the cluster. In all other closely checked cases, X-ray emission of galaxies with X-luminosities above  $10^{42}$  erg/s appears to be related to AGNs with the most luminous sources naturally arising in quasars.



**Fig. 1.** The boxes indicate the correlation between  $L_X$  and  $L_{\text{blue}}$  for elliptical galaxies (solid line; from ref. [14]; dashed: from ref. [12]). The open circle gives the minimum observed (0.1 – 2.4 keV) X-ray luminosity of NGC 6240, the filled circle represents the two-component model adopted in [76] (last row of their Table 2)

Taking the extended sources around ellipticals as a quasistationary thermal X-ray bubble one obtains a typical temperature  $T \geq 7 \cdot 10^6$  K, size of  $\sim 50$  kpc, mass of the hot gas of  $10^{10} M_\odot$  and a mass of  $\sim 10^{12} M_\odot$  necessary to gravitationally bind the bubble. The cooling time will exceed  $10^9$  yrs for pressures  $nT \sim 10^4$  K cm $^{-3}$ . While the cooling is mostly radiative via bremsstrahlung, recombination and line transitions, the usually considered heating sources are gain of gravitational energy, supernova explosions and stellar-velocity dispersion ( $\sigma_*$ ) induced shocks of the gas released by stellar mass loss. The latter mechanism is supported by the above quoted temperature and the measured  $\sigma_*$  because it fits to the virial temperature of the stars  $T_{\text{vir}} = (\mu m_p / k) \sigma_*^2 \sim 7 \cdot 10^6 (\sigma_* / 300 \text{ km/s})^2$ . However, there is a debate in the literature whether detailed hydrodynamical models are able to match this simple model (e.g. [61]). In Sect. 1.2 we speculated about a possible relationship of the extended X-ray source to the formation history of the elliptical and its central MBH, an idea that will be further discussed elsewhere.



### 3 Early ULIRGs – pre-stages of ellipticals and MBH cores?

Recently, careful reduction procedures applied to the *COBE* data base led to a reliable detection of the apparently cosmological FIR background radiation between  $140\mu m$  and  $5000\mu m$  and its spectral shape [24], [28]. Modelled by direct stellar light plus dust-reprocessed stellar radiation, notably from star-forming regions, the *COBE* data require about twice the star formation rate at  $z = 1.5$  as that inferred from optical-UV observations. The ‘added’ FIR emission is likely to arise in dust-enshrouded galaxies or star-forming regions and is consistent with being represented by ULIRG-type spectra. A number of such ‘ULIRGs at high  $z$ ’ (which we like to call *early mergers*) with typical  $L \sim 3 \cdot 10^{12}$  erg/s appear to have been detected with the *SCUBA* sub-mm array on the 15m James Clerk Maxwell Telescope [4], [53]. Although the evidence for each case rests on probabilistic identifications and redshifts derived at optical/NIR wavelengths the result appears to be statistically convincing. Some disturbed morphologies strengthen the identification with early ULIRGs. Lilly et al. [53] believe that “these sources, producing at least 10% of all stars in the universe with star-formation rates of order  $300M_{\odot} \text{ yr}^{-1}$ , are plausibly identified with galaxies forming the bulk of their metal-rich spheroidal component stars.”

However, the FIR radiation is emission reprocessed by dust so that the true heating source at lower wavelengths is concealed. For simplicity it is being attributed solely to star formation. In local ULIRGs there is an ongoing debate whether AGNs do partly contribute to the FIR power [74].

Observationally it appears that the power of LIRGs (luminous infrared galaxies,  $L_{\text{FIR}} < 10^{12} L_{\odot}$ ) can be explained by predominant star-formation and that the evidence for an AGN contribution increases with FIR luminosity (e.g. [81], [58], [72]; see [74] and [34] for recent reviews). In particular, essentially all of the HyLIRGs (hyperluminous infrared galaxies,  $L_{\text{FIR}} \gg 10^{12} L_{\odot}$ ) seem to contain quasars [38]. In the ‘transition region’ around  $L_{\text{FIR}} \simeq 10^{12} L_{\odot}$  it then requires a careful object-by-object analysis to find out the major power source.

As in local mergers, MBHs might have grown in early mergers as well. We shall return to this point in the concluding section after having described the case for an AGN in a local ULIRG which we consider as a prototype.

### 4 An obscured AGN in the ULIRG NGC 6240?

With a redshift  $z = 0.024$  and a far-infrared luminosity of  $\sim 10^{12} L_{\odot}$  (cf. [93]), NGC 6240 is one of the nearest members of the class of ULIRGs (although due to changes of the methods to integrate over the wide IRAS bands and the adopted value of  $H_0$ , most authors now attribute an IR luminosity  $< 10^{12} L_{\odot}$  to NGC 6240 rendering it a LIRG instead of a ULIRG; favoring a small  $H_0$

and considering it more typical for the ‘upper class’ we continue to call it an ULIRG). This object has remarkable properties: its infrared  $H_2$   $2.121\mu\text{m}$  and  $[\text{FeII}]$   $1.644\mu\text{m}$  line luminosities and the ratio of  $H_2$  to bolometric luminosities are the largest currently known [90]; its apparent tidal tails and loops [29] and a double nucleus [33] complemented by its large stellar velocity dispersion of 360 km/s (among the highest values ever found in the center of a galaxy, [22]) suggest that it is a merging system on its way to become an elliptical. Like other ULIRGs, the object contains a compact, only  $\sim 10^2$  pc large, luminous CO(1-0) emitting core of molecular gas [85]. Within this core most of the ultimate power source of the FIR radiation appears to be hidden.

Concerning NGC 6240, at least four types of power sources have been suggested: Heating of dust by a superluminous starburst, by an AGN, by an old stellar population, and by UV radiation from molecular cloud collisions. In particular, previous hints for an AGN included (i) the strength of near-infrared recombination lines [20], (ii) the presence of compact bright radio cores [15] (iii) the discovery of a high-excitation core in the southern nucleus with *HST* [2], [3], [69], and the detection of the  $[\text{OIV}]$   $25.9\mu\text{m}$  emission line with *ISO* [57].

None of these arguments is watertight: (i) modified starburst models and special extinction situations could explain the near-infrared hydrogen recombination lines; (ii) a special arrangement of young radio supernovae could account for the compact radio sources [18]; (iii) the high-excitation core could be due to a ‘young flame’ of star formation in an older environment; (iv) the high-excitation  $[\text{OIV}]$   $25.9\mu\text{m}$  line has been found in some starburst galaxies as well [59].

In this contribution we emphasize the role of X-rays as a powerful tool to obtain clues for both an AGN and starburst-superwind activity. We discuss the evidence for a hard X-ray component in the *ROSAT* PSPC spectrum of NGC 6240 [76] as well as the discovery of luminous extended emission based on *ROSAT* HRI data [45] in combination with the observation of an FeK line and a hard X-ray component by *ASCA* (first reported by Mitsuda (1995, [63]). Altogether, these findings strongly suggest the presence of an obscured AGN.

Luminosities given here correspond to  $H_0 = 50$  km/s/Mpc.

#### 4.1 The X-ray spectrum of NGC 6240

The *ROSAT* PSPC spectrum of NGC 6240 could not be satisfactorily reproduced by a *one-component* fit [76]. E.g., a single Raymond-Smith model requires a huge absorbing column along the line-of-sight, the consequence being an intrinsic (absorption corrected) luminosity of  $L_{\text{X},0.1-2.4} \simeq 4 \cdot 10^{43}$  erg/s, practically impossible to be reached in any starburst-superwind scenario adjusted to the optical observations of NGC 6240. Our checks with a variety of fits confirm Fricke & Papaderos (1996, [32]) who had claimed  $3.8 \cdot 10^{42}$  erg/s with a thermal bremsstrahlung model. We found an excellent estimate of a

lower limit of the intrinsically emitted X-ray luminosity by fitting a single black body that did not require excess absorption:  $L_X \gtrsim 2.5 \cdot 10^{42}$  erg/s in the (0.1-2.4) keV band (dealing with  $H_0$  and other uncertainties yields a rather firm lower limit  $1 \cdot 10^{42}$  erg/s). However, *acceptable fits* require at least *two-components* one of which has to be a *hard* X-ray component that can be represented by either very hot thermal emission ( $kT \simeq 7$  keV) or a powerlaw. This applies for solar abundances or not too far from solar.

Admittedly, a second component in the *ROSAT* band could be omitted if strongly depleted metal abundances are adopted. At the present stage of the art of modelling (see the discussion in Komossa & Schulz (1998, [43]) and Buote & Fabian (1998, [13])), we consider such a solution as unlikely for NGC 6240. We are more concerned about other changes in the models due to future theoretical improvements.

The two-component fits yield a luminosity of the hard *ROSAT* component of a few  $10^{42}$  erg/s, at least  $1 \cdot 10^{42}$  erg/s. Due to the largeness of this luminosity we regard the hard component as *ultimately* arising in an AGN, i.e. as a scattered AGN component. Various fits of *ASCA* spectra (e.g., [63], [40], [39], [67]) reveal the extension of the hard component up to 10 keV. Hence, the presence of a rather hard and luminous component is well substantiated although there are some clear differences in the fits of the various authors. The approaches differ in the description of the soft component(s) and the amount of absorption of the hard component. In any case, it is striking that the luminosity of the (2 – 10) keV radiation amounts to a few  $10^{42}$  erg/s as well.

As we saw above, from UV to radio wavelengths, no convincing evidence has been found for a *directly seen* AGN, but circumstantial evidence for the presence of an *obscured* AGN. The first analysis of the *ASCA* spectrum of NGC 6240 already revealed a conspicuous FeK line complex with a high equivalent width of  $\sim 2$  keV typical for an AGN with some sort of scattering geometry. The *ASCA* spectrum resembles that of NGC 1068, the well studied ‘prototype’ of a hidden AGN [87]. Adopting the same scattering geometry as in NGC 1068 the *intrinsic* X-ray luminosity should be about  $\sim 10^2$  times larger than that of the observed scattered radiation, yielding at least  $\sim 10^{44}$  erg/s for the hard component which translates into  $L_{\text{bol}}(\text{AGN}) \sim 10^{45}$  erg/s. This means that the AGN contributes an appreciable part of  $L_{\text{FIR}} \sim 4 \cdot 10^{45}$  erg/s. A similar result was obtained from *ROSAT* data by us by guessing the scattering geometry from the optically visible apparent H $\alpha$  cone [76]. Also, another type of scattering model, with FeK $\alpha$  arising in a highly ionized near nuclear ‘warm scatterer’ (in other directions it would appear as a ‘warm absorber’) would require a similarly luminous AGN [45]. The latter model, which was suggested to explain the hard component, bears some similarities to the one suggested by Netzer et al. (1998, [67]).

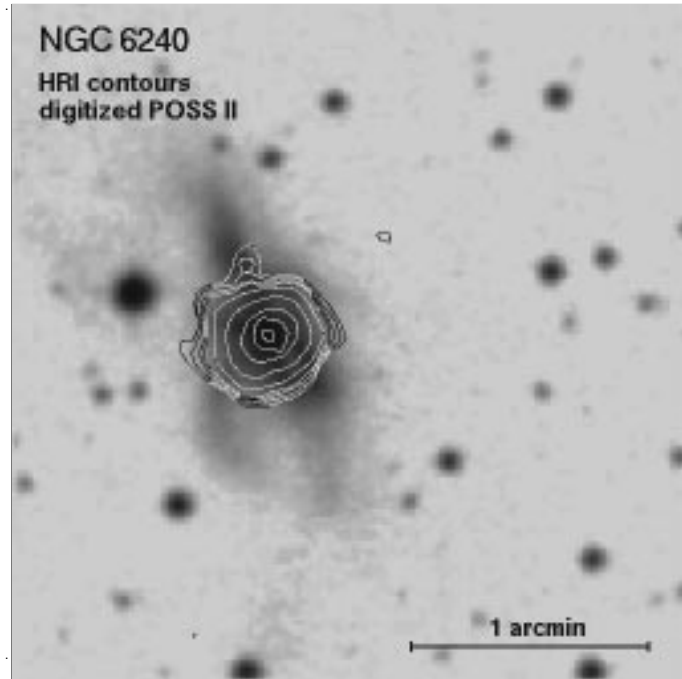
However, Netzer et al. explained the *whole ASCA* spectrum in terms of scattering and this seems to be ruled by the huge extent of the X-ray source

(> 25 kpc) disclosed in ref. [45] with the *ROSAT* HRI. We showed that efficient scattering can only be made with a small scatterer [76]. A small scatterer and an AGN are nearly inevitable if the X-ray variability detected in ref. [45] is confirmed. So far, the significance of the variations is only taken with some caution because it rests on measurements with different instruments.

Summarizing, the presence of the hard X-component and the high equivalent width FeK $\alpha$  provide excellent complementary evidence for an obscured AGN in addition to the less compelling indications cited in the introduction to Sect. 4. After briefly commenting on the *extended* X-ray emission we shall discuss the consequences.

#### 4.2 Extended X-ray emission

The HRI *images* [45] reveal that part of the huge X-ray luminosity arises in a roughly spherical source with strong ( $\geq 2\sigma$  above background) emission out to a radius of  $20''$  ( $\sim 14$  kpc; Fig. 2). Hence, NGC 6240 is the host of one of the



**Fig. 2.** *ROSAT* HRI X-ray contours overlaid on a Palomar Sky survey image of NGC 6240. The outermost contour is at  $2\sigma$  above the background of the X-ray frame

*most luminous extended* X-ray sources in isolated galaxies (see Fig. 1 where  $L_X$  is compared with a sample of elliptical galaxies and Arp 220). Analytical estimates based on the Mac Low & McCray (1988, [60]) models show that the *extended* emission can be accounted for by superwind-shell interaction from the central starburst [76].

However, unless the starburst source is off-center this scenario lets one expect a bipolar rather than the observed near-circular symmetry of the X-ray source. Could the X-ray bubble have been formed due to expansion of some of the merger-induced infalling gas because of incomplete cooling? Considering that NGC 6240 is on its way to become an elliptical we [44] [77] mentioned a few further possibilities like heating by the large velocity dispersion of (350 – 360) km/s ([52], [22]) or that the bubble might have been caught in the verge of experiencing its central cooling catastrophe [17] [31]. Shocks induced by a cooling flow might also help to explain the LINER-like line ratios in the central few kpc and, with lower velocities, excite the molecular cloud complex between the nuclei leading to the extreme  $H_2$  luminosity found there [90].

### 4.3 Inferences on the MBH in NGC 6240

In the interpretation suggested above, the *extended* X-ray emission is not influenced by the present AGN which could only contribute to a *near-nuclear* scattered component. In Sect. 4.1 we derived  $L_{\text{bol}}(\text{AGN}) \sim 10^{45}$  erg/s. Assuming that this value is close to the Eddington luminosity, a black-hole mass of  $M_{\text{MBH}} \simeq 10^7 M_\odot$  results.

One might argue that the present black hole mass could be  $\gg 10^7 M_\odot$  while the accretion rate is significantly below the Eddington rate. However, in the simplest scenarios a low feeding rate is unexpected in an object where plenty of fuel is available, and where the infall-triggering forces are present. We therefore consider  $M_{\text{MBH}} \sim 10^7 M_\odot$  as the currently best estimate for NGC 6240.

NGC 6240 is expected to form an elliptical galaxy of  $10^{11-12} M_\odot$  after having completed its merging epoch [82]. Since the relation [51]

$$M_{\text{MBH}} \approx 0.002 M_{\text{gal}} \quad (2)$$

valid for the evolved elliptical, predicts  $M_{\text{MBH}} \sim 10^{8-9} M_\odot$  the black hole has still to grow by one or two orders of magnitude.

Equalizing a typical accretion luminosity  $L_{\text{acc}} = 10^{46} (\text{d}M/\text{d}t)/(1M_\odot/\text{yr})$  erg/s with the Eddington luminosity  $L_{\text{Edd}} = 1.3 \cdot 10^{38} (M/M_\odot)$  erg/s we get an “Eddington accretion rate”  $\text{d}M/\text{d}t = 7.7 \cdot 10^{-9} M$  if  $t$  is measured in years and  $M$  in  $M_\odot$ . Integrating this equation leads to exponential growth with

$$M = M_{\text{init}} 10^{t/3 \cdot 10^8 \text{yr}} \quad (3)$$

Consequently, under optimal conditions the MBH could grow to  $\sim 10^9 M_\odot$  within  $6 \cdot 10^8$  yr although, in practice, a longer time scale is expected. The fuel for the growth of the MBH finally comes from the  $10^{10} M_\odot$  of molecular gas residing in the core of NGC 6240 [85]. According to these simple budget considerations there appears to be no difficulty in obtaining the expected mass of the black hole in the resulting elliptical.

However, many details of the actual astrophysical MBH-growth processes have still to be worked out. As yet, some authors (e.g. [86]) believe that mergers usually convert galactic disks to bulges without any corresponding change in the prior black hole mass while others (like us) take it for granted that the merger event leads to rapid growth of the black hole(s). Recently, Wang & Biermann [91] showed by a beautiful accretion model that the empirical relation Eq. 2 can be understood quite well if one takes the competitive feeding of starburst and MBH into account.

## 5 Concluding discussion and outlook

The particular merger NGC 6240 has so far revealed several strong clues for the presence of an AGN and may be a rosetta stone. In addition to MBH evidence, it exposes a gigantic luminous extended X-ray source similar to the X-ray sources of ellipticals. Therefore we suggested ingredients beyond a standard starburst outflow model (Sect. 4.2), among those that the bubble reflects part of the energy from the infall history of the ISM of this galaxy. The compressed molecular gas core provides the fuel for the central MBH, giving rise to AGN activity.

Has the MBH been formed during the merger or was there a black hole before? The correlation [51] between black hole mass and mass of the spheroid and the statistical consistency with MBHs being a common component of spheroids (bulges and ellipticals) (Sect. 1.3) suggests a hierarchical picture: spiral bulges contain MBHs that will be seeds for a bigger MBH formed in a merger that evolves into an elliptical. Thus it is one (or two) preexisting MBH(s) that is (are) growing in NGC 6240.

In this vein, mergers of lower-mass galaxies produce lower-mass MBHs, while the most luminous AGNs are expected in encounters of very massive objects. Because the molecular material in the central  $\sim 10^2$  pc will form a disk, the visibility of the AGN depends on the viewing angle and the accretion mode. To satisfy eq. 2, about a few percent of the central gas has to be dumped onto the growing MBH, most of the rest has to be consumed by the starburst to lead to a gas-poor elliptical. As long as the starburst lasts, the AGN will not be the dominating luminosity source of the ULIRG.

Can this picture be transformed to much earlier epochs of the universe when most of the massive ellipticals had been formed? So far, Hubble deep field observations, the *COBE* infrared background and *SCUBA* sub-mm identifications of infrared luminous high- $z$  galaxies observations broadly support

a hierarchical galaxy formation picture that was theoretically developed as a kind of cold dark matter structure formation [92], [41], [6]. The merging of baryonic material occurs in cold-dark matter halos that had been earlier assembled by merging processes as well.

Concerning MBH formation, sceptics argue that the peak of the number of luminous quasars at high  $z$  is hard to understand in a hierarchical scenario because low-mass black holes form first and MBHs will grow by the course of time. This simple argument is opposed by Haehnelt & Rees [36] who, in their quasar-evolution scheme, showed that a MBH-formation efficiency (parametrized by  $M_{\text{MBH}}/M_{\text{Halo}}$ ) proportional to a high power of  $(1+z)$  is conceivable. Observationally, counts of galaxies suggests a growth of the pair density with a power of  $(1+z)$  leading to a correspondingly higher merger rate.

However, “early mergers” (i.e., at high  $z$ ) are likely to be quite different from mergers today. The numerical studies focus on detailed Monte-Carlo treatment of the dark-matter component and treat the baryonic gas only in a schematic way. Detailed studies of nearby mergers are important in order to learn more physics to be included in the simulations of forming and evolving galaxies.

Our scheme in which MBHs are evolving during the assemblage of the spheroidal components of galaxies has to start with some kind of seed black holes. The Eddington growth rate of Eq. 3 can be taken as a crude upper limit for MBH growth. Starting with the Eisenstein-Loeb [26] seeds of  $\sim 10^6 M_{\odot}$  (Sect. 1.1) we need three to four 10-folding times for  $M_{\text{MBH}} = 10^{9-10} M_{\odot}$ , i.e. at least  $\sim 10^9$  yrs. Such massive MBHs exist at  $z \sim 5$ , the Eisenstein-Loeb seeds were formed beyond  $z \sim 10$ . Table 1 shows that this growth requirement excludes an Einstein-de Sitter Universe ( $q_0 = 0.5$ ) and calls for a tenuous open universe with a low value of  $q_0$  unless the universe is accelerating. A more precise statement on the allowed world models is not warranted without simultaneously modelling structure formation.

In any case, time scales are tight, hopefully also for the new telescopes and instruments that will help us to verify or modify the picture of formation and evolution of spheroids and massive black holes outlined above.

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A preprint of this and related papers can be retrieved from our webpage at <http://www.xray.mpe.mpg.de/~skomossa/>

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